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SUMMARY

A flow visualization technique for the large wind tunnels of the National Full-Scale Aerodynamics Complex (NFAC) is described. The technique uses a laser sheet generated by the NFAC Long-Range Laser Velocimeter (LRLV) to illuminate a smoke-like tracer in the flow. The LRLV optical system is modified slightly, and a scanned mirror is added to generate the sheet. These modifications are described, in addition to the results of an initial performance test conducted in the 80-by 120-Foot Wind Tunnel. During this test, flow visualization was performed in the wake region behind a truck as part of a vehicle drag reduction study. The problems encountered during the test are discussed, in addition to the recommended improvements needed to enhance the performance of the technique for future applications.

INTRODUCTION

Flow visualization is an important experimental technique used in wind tunnel research for understanding fundamental fluid mechanics. It is a technique which has been used extensively in the past. As early as 1883, Osborne Reynolds used colored dyes in his experiments which enabled him to detect transition from laminar to turbulent flow in water (ref. 1). Wind tunnel applications date back to Ludwig Mach's work in 1893 using a 180- by 250-mm indraft wind tunnel (ref. 2). Flow visualization continues to be an important tool for aerodynamic research today and is often the first step taken to gain understanding of an aerodynamic problem.

Large portions of a flow are often visualized to provide qualitative data about the general flow pattern. This data can then be used to identify areas of particular interest where more detailed quantitative measurements are needed. An experimental investigation can therefore be made more efficient by concentrating measurements in these areas and by reducing or eliminating measurements in areas determined to be less important.

One of the many techniques which have been used successfully by investigators is visualization of the flow by laser sheet (refs. 3-9). This technique relies on the introduction of a tracer material that scatters light and the use of a thin sheet of collimated laser light to illuminate the area of interest. The intense light of the laser sheet is scattered by the tracer material and enables the observer to see a two-dimensional slice of the flow.

The slice can have almost any desired orientation limited only by the optical access required for the sheet. When the slice is oriented parallel to the flow direction, a view similar to that of the smoke-wire technique is obtained (ref. 9). By selecting other sheet orientations, unique views are obtained that are generally not available using other techniques (refs. 8,9).

The laser sheet is usually created using one or more cylindrical lenses (refs. 3-9). These lenses spread the beam into a thin, divergent, or fan-shaped sheet. Unfortunately, the light intensity in the resulting sheet is distributed nonuniformly. In the direction perpendicular to propagation, its intensity varies in a Gaussian manner similar to the incident beam. In the direction of propagation, its

intensity decreases in proportion to the rate of spreading because the beam energy is spread over a larger and larger volume.

These nonuniformities can cause problems when photographic or video images of the sheet are desired. Normally only the central portion of the sheet is used because intensity falls rapidly toward the edges. Consequently, to cover a given region of the flow, a wider angle of spread is required. The overall light intensity drops accordingly and longer exposures are necessary to record images of the tracer (ref. 10). The result is a general decrease in the ability of the technique to freeze rapid fluctuations if the required exposure is long compared to the period of the fluctuations.

This report describes a different method of generating the laser sheet. Instead of using cylindrical optics to create a stationary sheet, it is proposed that the sheet be created by scanning the beam rapidly through an arc. A uniform distribution of light intensity across the sheet is generated simply by scanning the beam with uniform velocity. Since the flow and tracer are exposed to the full intensity of the collimated beam at a given point, much shorter effective exposures are necessary for the same flow conditions, laser power, and tracer concentration.

This technique was first used to visualize the wake behind a full-size tractor trailer (hereafter referred to as truck) in the National Full-Scale Aerodynamics Complex (NFAC) 80- by 120-Foot Wind Tunnel. The test was conducted in October 1988 and was undertaken to study the base drag of the truck with and without various modifications. Scale and pressure data were taken in addition to the flow visualization data but are not included in this report (these will be included in a publication by others).

EXPERIMENTAL SETUP

A photograph of the truck installation in the 80- by 120-Foot Wind Tunnel test section is shown in figure 1. The experimental investigation consisted of 64 runs performed at speeds of 50 and 80 knots. During the course of the test, 45 different configurations of the truck were tested. Each involved small changes or additions to the baseline configuration. Two configurations were selected for further study using flow visualization: the baseline configuration and the configuration found to have minimum drag.

The laser sheet was generated using the NFAC Long-Range Laser Velocimeter (LRLV) instrument. A sketch of the test section installation showing a typical orientation of the laser sheet is shown in figure 2. The LRLV system was developed to perform laser Doppler velocimeter flow surveys and is described in detail in reference 11. Minor modification of the existing unit was made in order to add the light-sheet capability.

Figure 3(a) shows a diagram of the LRLV transmitting optics in the configuration for laser Doppler velocimeter operation. The system is reconfigured for flow visualization by removing some of the optical components and adding a galvanometer scanner and stationary dielectric mirror. Figure 3(b) shows the transmitting optics with these changes.

The folding mirror can have four orientations in addition to the one shown. It can be mounted 45 or 90° to either side of the vertical axis. The rotational scan capability of the instrument (ref. 10) can be used to further position the sheet. During this investigation, the folding mirror was oriented 90° from the vertical position shown, in order to obtain a horizontal sheet. The instrument was then rotated to position the sheet as shown in figure 2.

The galvanometer scanner used to generate the sheet is connected to an electronic driver. This unit accepts an analog voltage input (± 4 volts peak-to-peak) to control the position of the mirror. A nearly uniform lateral light intensity distribution is obtained by introducing a triangle waveform. This waveform drives the mirror at nearly constant velocity and produces the laser sheet shown in figure 4.

The driver can accept frequencies from d.c. to 800 Hz. At low frequencies, a mirror displacement from the center position of up to $\pm 10^\circ$ is possible, which produces a wedge-shaped sheet having a 40° vertex angle. At higher frequencies, this maximum angle decreases due to the inertia of the mirror and its mount. A 20° sheet vertex angle was used during this investigation with the beam oscillating at a frequency of 100 Hz.

A commercial smoke generator was used to create the required tracer for flow visualization. This device was installed inside the trailer at the aft end near the rear doors and was remotely controlled from the wind tunnel control room. When the unit was actuated, smoke flowed through a flexible tube and was introduced into the flow through a hole in the left rear door of the trailer. The smoke density could be controlled remotely. After some initial experimentation, a level near minimum density was selected for the flow visualization. A cutaway view of the trailer showing the smoke generator is shown in figure 5.

A still camera and two video cameras were used to record the image of the flow visualization on film and video tape. These cameras were placed on the east and west walls and at the ceiling of the test section outside the flowfield, as shown in figure 6. The still camera was located at the west-wall viewport, and the video cameras were located at the other two viewports.

The still camera used 70mm, 400 ASA black-and-white film and was equipped with a 150mm, f/3.5 lens. Low light levels required the photographs to be taken with the aperture wide open at a shutter speed of 1/4 sec.

Both video cameras were of the CCD (charged-coupled device) array type. Each used a single-chip interline transfer CCD array with integrated color filter and had 574 horizontal and 499 vertical pixels (525 lines, 60 fields/sec, 30 frames/sec). The frame exposure time for this type of camera occurs over a 1/30-sec interval during which photons incident on the photo sensor sites of the CCD array produce an accumulation of electrons at the sites. These accumulations are transferred to opaqued shift registers and then read out completely as two fields during the exposure time of the next frame; i.e., the two fields are exposed simultaneously over the 1/30-sec interval and represent a record of the integrated radiant exposure during this interval.

The horizontal resolution of the cameras is specified to be 380 lines at the center of the frame. Each was equipped with a 10.5- to 84-mm zoom lens with auto aperture control from $f/1.4$ to $f/22$. The auto aperture control was disabled, however, and set open to $f/1.4$ for the duration of the test.

Two u-matic format video cassette recorders were used to record the images taken by video cameras. They used a rotary two-head system and operated at a tape speed of 9.53 cm/sec.

RESULTS AND DISCUSSION

This test was undertaken to study the base drag of the general truck configuration shown in figure 1 and to examine what drag reductions could be achieved by making small changes to the baseline configuration. During the course of the test, flow visualization data were taken in addition to other data such as surface pressures and vehicle forces. The following discussion addresses only the flow visualization results and focuses on the mechanics of the technique.

The photograph of figure 7 shows the laser sheet in its location downstream of the truck aft end. The sheet is shown at nearly horizontal orientation and was made visible using smoke from the smoke generator for the photograph. During data acquisition, the sheet was tilted to the horizontal center of the truck aft end using the positioning capability of the LRLV.

Still photographs were taken from the west-wall viewport location. Light levels proved to be inadequate for acceptable images due to the poor viewing angle from this location, which is nearly backscatter. The photographs were taken with the tunnel lights shut off in the rear two-thirds of the test section and with laser power set at 7 W. For this light level, a relatively long exposure of $1/4$ sec was selected using the 1.50-mm lens at $f/3.5$ for the first series of photographs. Unfortunately, even this long exposure proved to be inadequate for imaging the sheet and no further photographs were taken from this angle.

Video images were recorded using the video cameras located at the ceiling and east-wall viewports. These cameras had a fixed shutter speed of $1/30$ sec per frame, according to video standards. To achieve the correct exposure, the lens aperture was held fixed at $f/1.4$, with the same test section lighting conditions as for the still photographs.

Light levels proved to be marginal for the ceiling camera. Some detail is visible in the video recording from this camera, but contrast between the smoke and background is generally poor. Improvement would probably have been possible if more of the test section lights could have been turned off. Unfortunately, operational procedures prevented more lights from being extinguished.

Sufficient scattered light intensity was observed from the east-wall viewport location. This viewing angle is nearly forward scatter, the direction expected to give best performance. In fact, light intensity of the imaged sheet from this angle was sufficiently high that a reduction in laser power was necessary to prevent saturation of the video signal. Power was reduced to about 4 W while beam scan frequency was maintained at 100 Hz.

Figure 8 shows a still photograph of a video frame taken from this location. Although the resolution of this image is not high, the wake region is clearly shown. Near the truck, a region of reverse flow is apparent where the smoke is most dense. Behind this region, an area of fairly stagnant air occurs where the smoke becomes less dense. Also plainly visible are the boundaries of the wake region. Along these boundaries, small vortical structures are clearly seen convecting downstream in the video recordings. Unfortunately, the still photograph in figure 8 does not show the structures as clearly.

A dark line is visible in the sheet near the aft surface of the truck where the sheet contacts the rear doors (fig. 8). This line is a small discontinuity or shadow in the sheet which could not be eliminated at the time of the test because of time constraints.

The selected 100-Hz scan frequency produced slightly more than six beam passes during the 1/30-sec exposure time of the video cameras (one beam pass occurs for each half cycle of the triangle waveform). For flows having rapid fluctuations in comparison to this scan frequency, potential smearing of the image is possible when multiple scans per frame occur. After six beam passes, for example, the frame image is essentially a sixfold exposure of the sheet because the overall exposure is cumulative on the CCD array. If the flow structure changes significantly between scans, blurring of the image may take place.

A single beam scan per video frame can be obtained by reducing the scan frequency to 15 Hz. To offset the decrease in scattered light, higher laser power may be necessary. Future visualizations should be attempted using a scan frequency of 15 Hz.

CONCLUSIONS

A technique for visualizing the flow in the large wind tunnels of the NFAC facility has been developed. This technique uses a scanned mirror, in place of more conventional cylindrical optics, to generate a laser sheet with nearly uniform lateral intensity. The scanner and laser are part of a modification to the Long-Range Laser Velocimeter system which has been used previously for laser Doppler velocity measurements.

The feasibility of using the technique in the facilities of the NFAC was studied in the 80- by 120-Foot Wind Tunnel by visualizing the wake region behind a truck as part of a vehicle drag study. The basic technique was found to be successful, but the method chosen for recording images of the sheet was identified as needing improvement. The following conclusions are drawn concerning the improvements required.

- 1) The viewing angle for still or video photography should be selected to achieve the condition of nearly forward scatter.
- 2) Ambient light levels in the test section should be reduced further, and higher-speed film should be used for the still photography.

3) The camera lenses should be chosen so as to fill the frame completely with the sheet image to obtain maximum detail.

4) The beam scan rate should be reduced to 15 Hz to obtain one beam pass per video frame for maximum image clarity. The still-camera shutter speed should be set to 1/30 sec for the same reason.

A second scanner will be added for future visualization applications. This scanner will be oriented orthogonally to the first. Additional capabilities will be made possible by properly driving the two scanners. These include creating multiple laser sheets and the sweeping of a single sheet.

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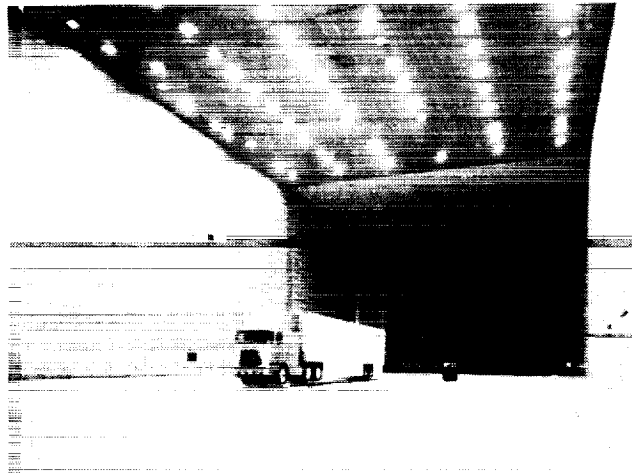


Figure 1. Test section of 80- by 120-Foot Wind Tunnel showing relative locations of the truck and laser system.

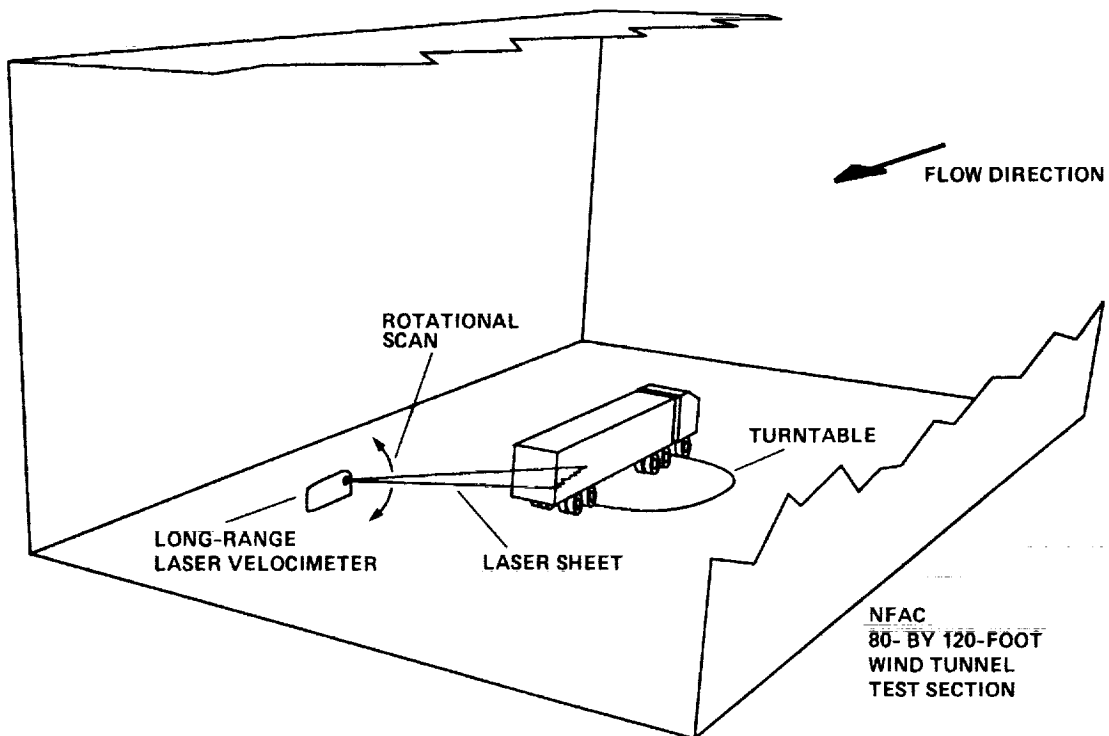


Figure 2. Perspective view of 80- by 120-Foot Wind Tunnel test section showing truck installation and typical orientation of laser sheet (drawn to scale).

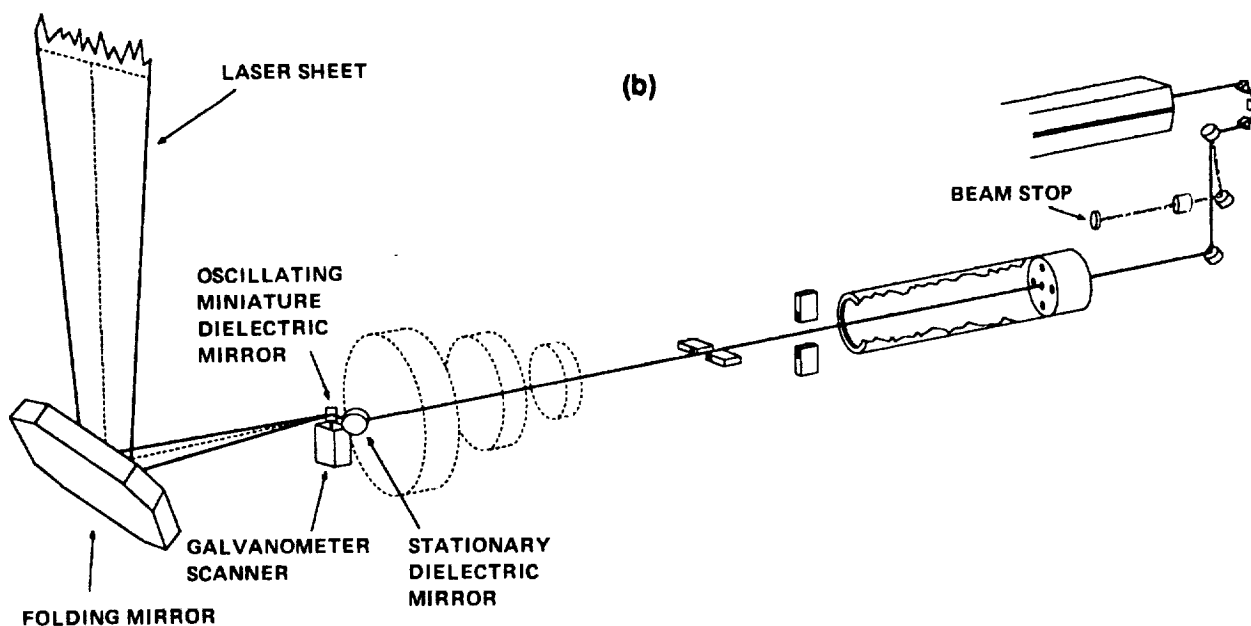
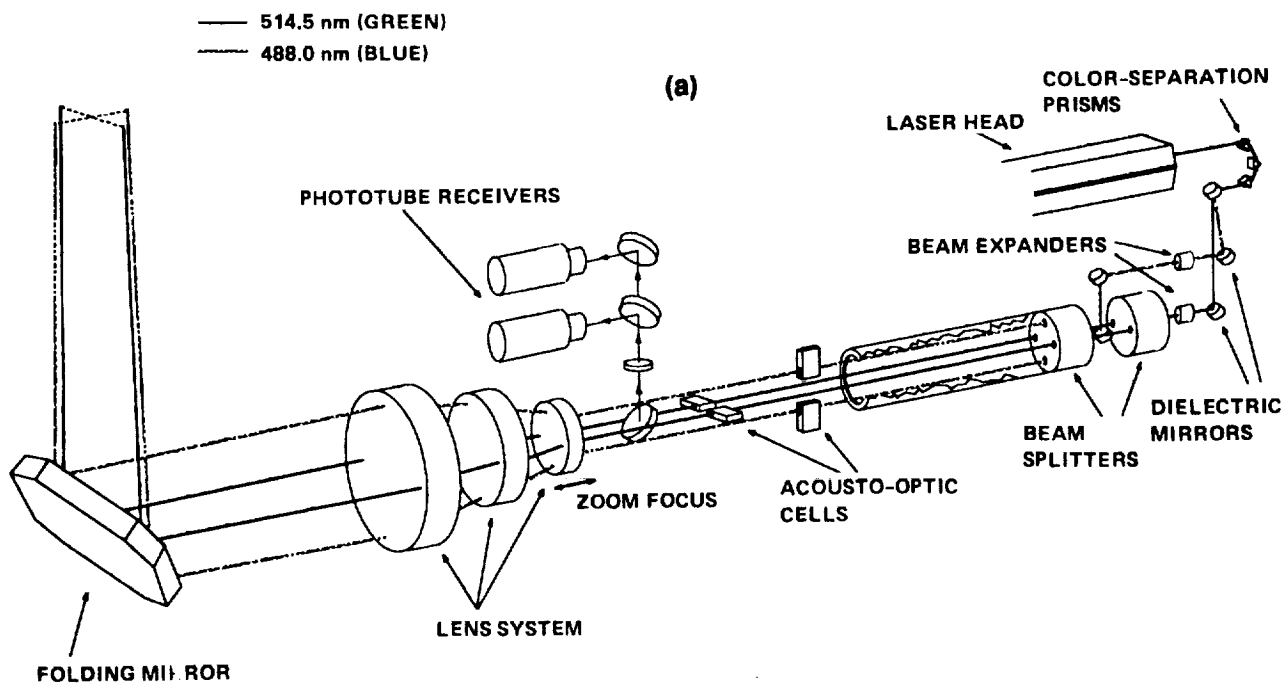


Figure 3. Internal optical components for transmission of (a) 4-beam pattern for laser velocimeter operation, (b) laser sheet for flow visualization.

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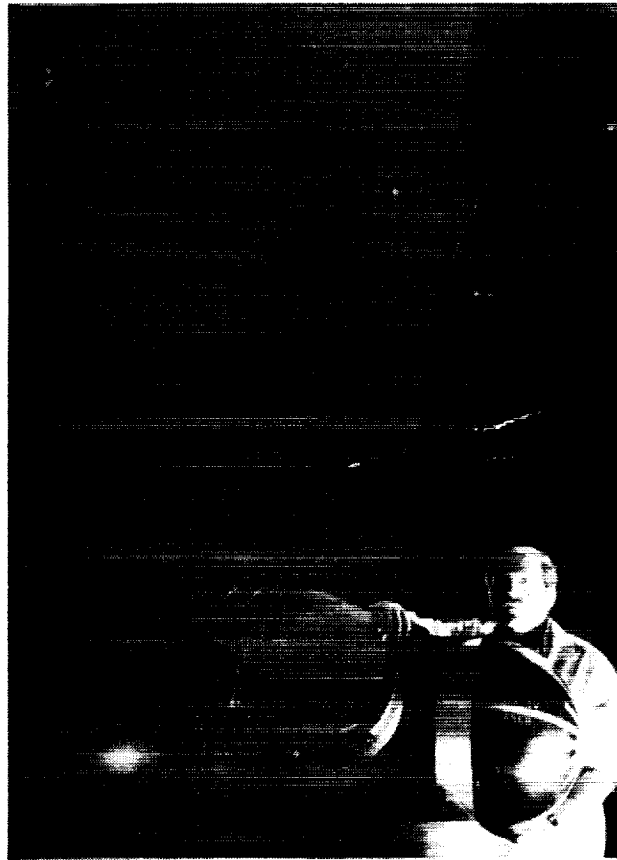


Figure 4. Closeup view of laser system showing laser sheet tilted 45° from horizontal orientation.

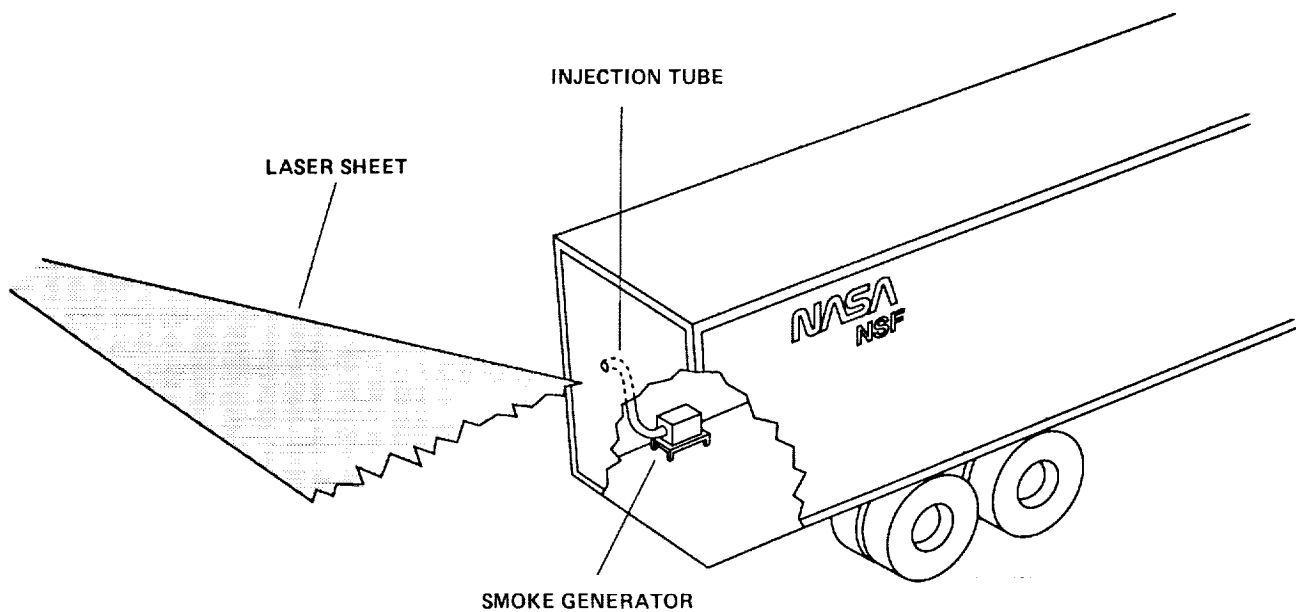


Figure 5. Location of smoke generator showing method of injection into flow.

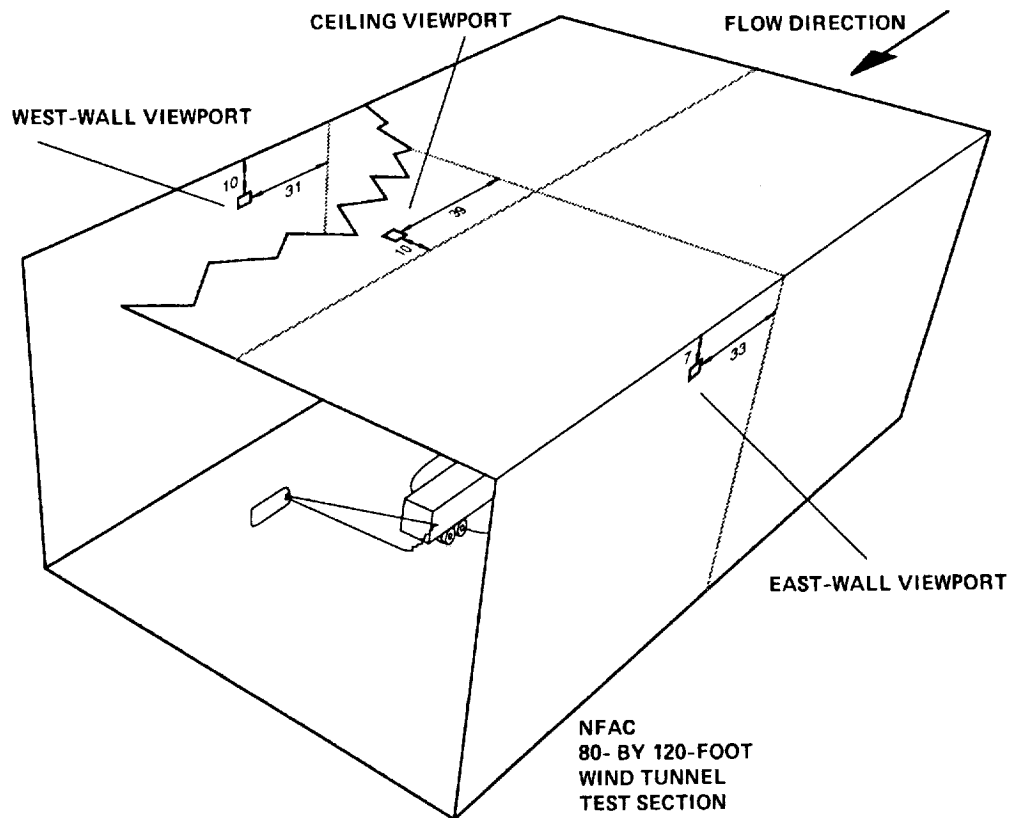


Figure 6. Perspective view of test section showing viewports where cameras were placed.

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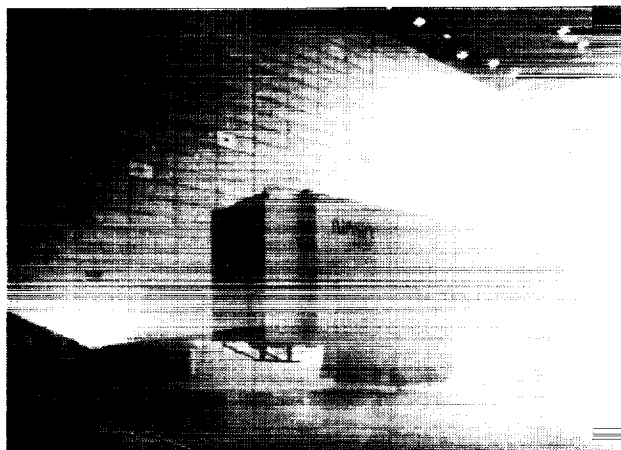


Figure 7. Laser sheet shown in nearly horizontal orientation at aft end of truck in 80- by 120-Foot Wind Tunnel test section.

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Figure 8. Video screen image of light sheet after smoke injection, showing wake behind truck (view from east-wall camera location).

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